EVALUATION AND CONTROL OF THE LONG-TERM WATER BALANCE ON AN URBAN DEVELOPMENT SITE

Bruce K. Ferguson, M. Morgan Ellington and P. Rexford Gonnsen

AUTHORS: Bruce K. Ferguson, M. Morgan Ellington and P. Rexford Gonnsen, respectively Associate Professor and Graduate Student, School of Environmental Design, University of Georgia, Athens, GA 30602, and Principal in Beall Gonnsen & Company, Athens, GA.
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INTRODUCTION

The long-term water balance is promising but previusly unused technique for evaluating and contolling the hydrologic effects of urban development. The water balance is a summary of all the inflows and outflows, over a period of time, of a land area such as a hillslope, a watershed or a political unit. The long-term water balance refers specifically to the average levels and seasonal fluctuations of flows over a period of years, indicating the overall pattern of interaction of a land area with the hydrologic environment. Although the water balance has long been a prominent concept in geography, where it is used as a summary index of the moisture and energy endowments of regional environments, its application to management of specific urban development projects has not been fully explored.

A more traditional approach to urban stormwater management is the design storm. Some design storms are defined by average recurrence intervals. Others are uniform storm phenomena, such as the first one or two inches of runoff from any storm. The application of this concept is appropriate for management of peak flood flows. Interest in flood contol has made the design storm essentially the exclusive approach to regulation of stormwater in Georgia. However, a design storm is not a significant part of the total water resources of an area; it does not indicate overall moisture endowments of the environment. For example, in northern Georgia, where the annual precipitation averages roughly 50 inches, a 10 year design storm is only about 6 inches in 24 hours. Thus the design storm lasts only a fraction of one percent of the elapsed time during its recurrence interval, and 500 inches of rain go by while stormwater facilities wait for the 6 inches for which they were designed. A broad interest in water resources demands a more comprehensive management of the stormwater resource.

The long-term water balance summarizes average seasonal patterns of hydrologic inputs, outputs and changes in storage. The long-term water balance could be used to evaluate such important specific long-term parameters as baseflow runoff, ground water recharge, and soil moisture levels. Through environmental connections between the hydrologic environment and vegetative and human communities, these parameters indicate potential levels of on-site and downstream water supplies, assimilative capacity, recreational resources, wetlands, and aquatic life. The application of the long-term water balance to a proposed urban development might suggest types of impacts and approaches to stormwater control that would not be considered by applying the design-storm idea alone. One control approach that deserves to be evaluated this way is infiltration, which uses closed basins to force runoff water to enter and be stored in subsurface soil voids (Ferguson, 1990a; Ferguson and Debo, 1990).

This paper presents preliminary development of a model for simulating the long-term water balance of urban development sites, and application of the model to a specific development to illustrate potential water-balance effects of urbanization and alternative methods of stormwater control.

PREVIOUS STUDIES

An early approach to the long-term water balance was that of Thornthwaite (Thornthwaite and Mather, 1955), who developed a "bookkeeping" procedure for partitioning monthly precipitation into soil moisture, evapotranspiration, and runoff. Thornthwaite's formulation has been widely applied to characterize the general physical endowments of geographic environments (Dunne and Leopold, 1978).

Among applications of Thornthwaite's concept to urban environments, Muller (1967) computed separate water balances for pervious and impervious surfaces in the Raritan River watershed, and averaged the result to obtain flow for the watershed as a whole. Kung and McCabe (1987) used a similar approach for four watersheds near Knoxville, Tennessee.

Another family of hydrologic models - continuous simulation models - use series of input data to estimate longer-term hydrologic behavior, the results of which can be analyzed statistically. The more sophisticated of these models are demanding of computing resources, but they have suggested many refinements in hydrologic modeling. CREAMS (Smith and Williams, 1980) is widely used for application to non-urban environments; it uses daily data to estimate evaporation, direct runoff, and base runoff. A variation upon CREAMS is Williams, Nicks and Arnold's (1985) SWRRB, which can accommodate subareas having different soils and land uses. A sophisticated continuous-simulation model with specifically urban components is that of the U.S. Geological Survey (Smith and Alley, 1981), which distinguishes impervious areas that are directly connected to the channel drainage system from those that drain onto pervious ground, where the runoff supplements precipitation. In Grimmond, Oke and Steyn's (1986) distinctive model, the land surface is divided into impervious, pervious irrigated, and pervious unirrigated zones; irrigation is added to precipitation on the irrigated zone, and urban enhancement of evapotranspiration is taken into account.

DEVELOPMENT OF MODEL

A water-balance model was desired that would be less demanding of data and computing resources than contemporary continuous simulation models, but capable of evaluating

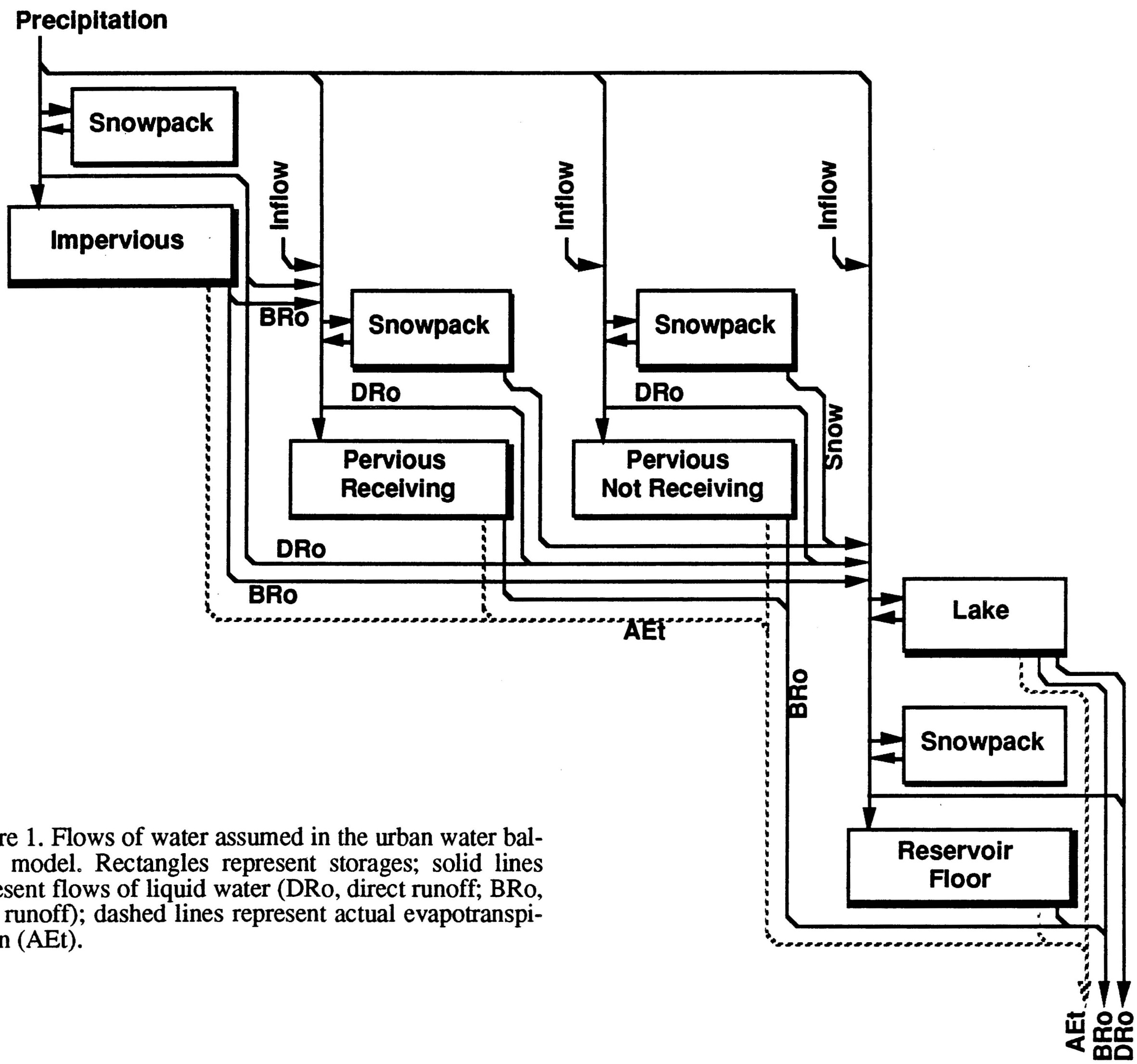

Figure 1. Flows of water assumed in the urban water balance model. Rectangles represent storages; solid lines represent flows of liquid water (DRo, direct runoff; BRo, base runoff); dashed lines represent actual evapotranspiration (AEt).

distinctively urban hydrologic phenomena including varying proportions of direct and base runoff, mosaics of pervious and impervious surfaces with runoff transferred between them, and the water-balance effects of stormwater control reservoirs.

Consequently a spreadsheet model was developed to adapt Thornthwaite's approach to the specific concerns of urban development sites. Monthly data are used, with no change in storage from year to year.

The model works on a watershed unit, with the watershed broken into four zones: impervious, pervious receiving runoff from impervious areas, pervious not receiving runoff, and reservoir. A specified proportion of runoff from the impervious zone drains directly to the reservoir, bypassing the pervious-receiving zone. Flows among the zones are summarized in Figure 1, where rectangles represent storages, solid lines represent flows of liquid water, and dashed lines represent evapotranspiration. Net discharges of direct runoff, base runoff and evapotranspiration are summed for the watershed as a whole.

A water balance is calculated in each zone. Snowpack storage is estimated by the method of Ferguson and Debo (1990): seasonal freezing builds the snowpack; later snowmelt supplements monthly precipitation. Direct runoff in each zone is estimated by the SCS method (U.S. Soil Conservation Service, 1972 and 1986), with monthly values of the SCS curve number assigned based on soil moisture level. All precipitation remaining after direct runoff becomes part of the soil moisture, eligible for evapotranspiration and base runoff according to Thornthwaite's accounting procedure. Monthly potential evapotranspiration is input by the user.

The reservoir zone's water balance is based on the routing procedure of Ferguson (1990a). A stormwater control reservoir may be specified by the user as either on the land surface, and susceptible to precipitation and evapotranspiration, or in an underground chamber, where such processes do not occur. The reservoir's horizontal and vertical dimensions are entered by the user. Lake storage can occur above the soil surface; remaining storage is carried over from month to month. By setting different infiltration rates and reservoir dimensions, a user could simulate an infiltration or detention basin with a dry or ephemeral regime (Ferguson, 1990a and 1990b) or a pond with stable water level; or the reservoir could be reduced to a nonfunctional point through which all flows pass unaltered.

For preliminary validation of the model, predicted and observed values for the watershed of the Middle Oconee River in Georgia were compared. Runoff data were from the gaging station near Athens (U.S. Geological Survey, 1987), and precipitation from the Athens airport. Of the annual precipitation of 50.2 inches, observed total runoff is equivalent to 17.8 inches per year, leaving 32.4 inches, or 65 percent, as evapotranspiration. Woodruff and Hewlett (1970) had estimated direct runoff in this area as between 6 and 8 percent of precipitation, using hydrograph separation.

Average precipitation and temperature data for Athens, Georgia were input to the model, with potential evapotranspiration estimated by the Thornthwaite method (Thornthwaite and Mather, 1955). SCS curve number was set at 65; impervious and pervious-receiving areas were each assumed one percent of the watershed area; reservoir area was zero. Soil available water holding capacity was set at 8.5 inches.

The model predicted total discharges well, but total runoff and direct runoff were slightly higher than observed, and evapotranspiration lower. The low Et could result from the Thornthwaite estimate of potential evapotranspiration; possibly use of a more rigorous estimation method could correct this error. The high direct runoff could result from the application of the SCS method on a monthly basis, considering that the method was produced to treat data on a daily basis; correcting this error will require refinement of the model. Although the results are quantitatively only approximate, they are believed to represent qualitative hydrologic processes adequately for a preliminary application to indicate directions of impacts accompanying land use change in the geographic area where the model was validated.

APPLICATION OF MODEL

The model was applied to the site of the Oconee County High School near Athens, Georgia. Of the site's 87 acres, 67 are drained by a single watershed. In this region, subsurface storage in deep residuum mediates long-term stream flows. Before development the site was in pasture and woodland. The proposed site plan indicated impervious surfaces totaling 21 percent of the site area, located mostly in the main watershed.

Two alternative plans for managing the site's post-development stormwater were developed. One plan discharged all stormwater from the site to the surface via culverts and a detention basin. The other plan infiltrated runoff from the bulk of the impervious surfaces near its source through stone-filled basins located under parking pavements. Each infiltration basin was sized, following the procedure described by Ferguson (1990) and Ferguson and Debo (1990), to hold average net monthly inflows plus some or all of the volume of the design storm.

Both plans were developed to reduce the peak rate of flow from the site's major watershed during the 25-year storm to the predevelopment level. In addition the infiltration plan was developed to reduce the total volume of flow during the same storm to the predevelopment level. Performance during the design storm was evaluated using the simulation program *On-Site Stormwater Management* (Ferguson and Debo, 1990), which generates storm hydrographs using the SCS method and routes flows through networks of channels and reservoirs.

Following design, both plans were evaluated by applying the long-term water balance model described above. The main watershed was divided into convenient subwatersheds; the water balance of each subwatershed was analyzed, and the results were summed for the site as a whole. For input to the model, average monthly precipitation and temperature were taken from National Oceanic and Atmospheric Administration data for the Athens airport. Potential evapotranspiration was estimated by the Thornthwaite method (Thornthwaite and Mather, 1955). Composite SCS curve numbers varied from 60 to 98, depending on proportions of soil covers in individual subwatersheds. Soil infiltration rates were based on subsoil textures (Ferguson and Debo, 1990) of clay and silt loam, which were taken from soil borings. Soil available water holding capacity was assumed 8.5 inches.

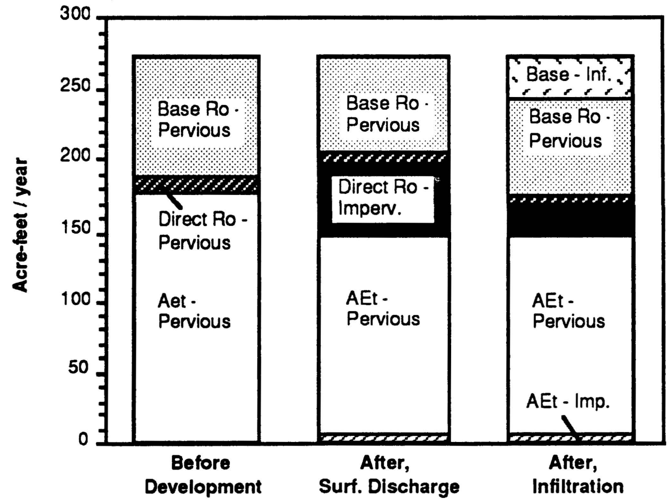

Figure 2. Predicted dispositions of water under alternative management scenarios in the main watershed of the Oconee County High School development site. (Ro, runoff; Imp., impervious; Inf., infiltration.)

RESULTS

The results of the long-term water balance estimates for the main watershed of the Oconee High School are summarized in Figure 2. Three management scenarios are compared: before development, after development with surface discharge, and after development with infiltration.In all cases the total annual disposition of water is 273 af/yr, equal to the average precipitation inflow. In each column, AEt is in the light tones at the bottom, direct runoff is in the dark tones in the middle, and base runoff is in the grey tones at the top.

Before development, with the site entirely in impervious cover, actual evapotranspiration (AEt) was about 65 percent of precipitation, as previously confirmed for this area. As expected for a well vegetated site, direct runoff is a small portion (12 percent) of total runoff.

After development with the detention (surface discharge) plan, AEt is reduced by the reduction of vegetated surfaces, despite the enhancement of soil moisture in some of the vegetated areas by runoff. Total annual runoff is correspondingly greater. About half of the runoff is in direct runoff due to the increased impervious surfaces; this is about six times greater than direct runoff before development. Base runoff is reduced in association with reduced pervious surface area.

With the infiltration plan, annual AEt was the same as with surface discharge, because soil covers were the same. But in this case both direct runoff and base runoff were greater than before development. The increase in base runoff results from the diversion of a large proportion of direct runoff from impervious areas into infiltration basins, where it is transformed into base runoff. The increase in direct runoff results from some impervious surfaces not draining into infiltration basins.

DISCUSSION AND CONCLUSIONS

Further refinement of the model described in this paper is desirable. In particular, the SCS method of direct runoff estimation was developed using peak annual daily data (Rallison and Miller, 1981); thus its application treats any rainfall increment as occurring all in one wet day, with presumably high levels of direct runoff compared with average monthly levels. In the long-term water balance model the SCS method could be adjusted to accommodate the lower average levels of soil moisture and direct runoff that probably occur over the course of a month. Further validation of all aspects of the model with observed data is necessary.

Despite the preliminary nature of the model, the results of this study are sufficient to suggest the following general conclusions:

1. The long-term water balance of urban development sites is important. The 273 af of precipitation falling on the main watershed of the Oconee County High School in an average year is a resource that is apportioned to various components of the environment. The School's development would cause an increase in total runoff. The partitioning of runoff between direct and base runoff is of great concern to groundwater recharge, flooding, recreation, aquatic life, and water supplies.
2. The long-term water balance of urban development sites is capable of being evaluated directly and efficiently using average monthly data. By applying a model such as that described in this paper, the long-term impacts of urban impervious surfaces and the effectiveness of alternative types of stormwater control can be estimated.
3. The long-term water balance of urban development sites is capable of being controlled. For years theory has predicted that infiltration should be capable of transforming direct runoff into base runoff. The results of this study begin to confirm that prediction. Stormwater management, which has typically focused on design storms, should emphasize as well control of the long-term water balance.

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